Assessing the risk of establishment and transient populations of *Spodoptera frugiperda* in Europe

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Supplementary material 1

S1. Full mathematical details of the model based on the Kolmogorov equation and temperature- and age-dependent parameters estimation

The model is described by a system of partial differential equations

$\frac{\partial \phi^i}{\partial t} + \frac{\partial}{\partial x}\left[v^i\big(T(t)\big)\phi^i - \sigma^i \frac{\partial \phi^i}{\partial x}\right] + m^i(t)\phi^i = 0, \quad t > 0,\ x \in (0,1),$

$\left[v^i\big(T(t)\big)\phi^i(t,x) - \sigma^i \frac{\partial \phi^i}{\partial x}\right]_{x=0} = F^i(t),$

$\left[-\sigma^i \frac{\partial \phi^i}{\partial x}\right]_{x=1} = 0,$

$\phi^i(0,x) = \hat{\phi}^i(x),$

with $i = 1, \dots, 4$ where $m^i(t)$ and $v^i\big(T(t)\big)$ are the stage-specific mortality and development rate functions, respectively. The unknown function $\phi^i(t,x)$ represents the number of individuals of the stage i at time t with physiological age $[x, x + dx]$. The functions $\hat{\phi}^i(x)$ represent the initial conditions of the model in terms of individual abundance in a certain stage, while the term σ^i is a diffusion coefficient, introduced to include the effects of stochasticity on the stage-specific development process. The functions $F^i(t)$ represent the fluxes of individuals from stage i to stage $i + 1$. For the egg stage, the input flux of individuals is represented by the fecundity rate function F^1 defined as follows

$$F^1(t) = g\big(T(t)\big)\left(1 - \frac{N^4(t)}{S + N^4(t)}\right)\int_0^1 \phi^4(t,x)h(x)\,dx$$

with $g\big(T(t)\big)$ describing the temperature-dependent component, $\left(1 - \frac{N^4(t)}{S+N^4(t)}\right)$ describing the density-dependent component, $h(x)$ describing the physiological age-dependent component, and $\phi^4(t,x)$ being the number of adult individuals at time t and physiological age x. For $i > 1$ the input flux of individuals is represented by

$$F^i(t) = v^{i-1}\big(T(t)\big)\,\phi^{i-1}(t,1), \qquad i = 2, 3, 4.$$

Fitting of the functions was performed using the function `lsqcurvefit` in MATLAB with termination tolerance on the first-order optimality, function value, and step tolerance set at 10^{-6}.

For brevity, in the following text, we omit in the description of the functions the reference to the stage $i = 1, \dots, 4$, unless strictly necessary, and we report the reference to the stage in tables and figures.

S1.1. Development rate function

The stage-specific and temperature-dependent development rate function $\nu(T(t))$ is described by the Brière function (Briere et al. 1999)

$$\nu\big(T(t)\big) = \begin{cases} rT(t)\big(T(t) - T_{inf}\big)\sqrt{T_{sup} - T(t)} & T_{inf} \le T(t) \le T_{sup} \\ 0 & otherwise \end{cases}$$

where $T(t)$ is the air temperature at time t, r is a scaling parameter, T_{inf} and T_{sup} represent the stage-specific minimum and maximum temperature thresholds at which development occurs, respectively. Parameters of development rate function $\nu(T(t))$ were estimated using the least square method on the experimental data related to the stage-specific development rates of *S. frugiperda* measured at different constant temperatures. Parameters of the development rate functions $\nu(T(t))$ and related figures for each stage are reported in Table S1 and Figure S1. The life-span of the adults was increased by reducing the development rate function $\nu^4\big(T(t)\big)$ by a fixed factor of 2.5 to obtain more realistic adult survival curves (He et al. 2021a; Zhang et al. 2021).

Table S1 Estimated parameters r, T_{inf} and T_{sup} of the temperature-dependent development rate function $\nu\big(T(t)\big)$ for eggs, larvae, pupae, and adults of *Spodoptera frugiperda*

Stage	$\boldsymbol{r}$	$\boldsymbol{T_{inf}}$ **(ºC)**	$\boldsymbol{T_{sup}}$ **(ºC)**
Eggs	$3.47 \cdot 10^{-4}$	10.6	34.9
Larvae	$5.18 \cdot 10^{-5}$	10.9	37.6
Pupae	$8.81 \cdot 10^{-5}$	12.2	40.0
Adults	$5.76 \cdot 10^{-5}$	5.2	40.0

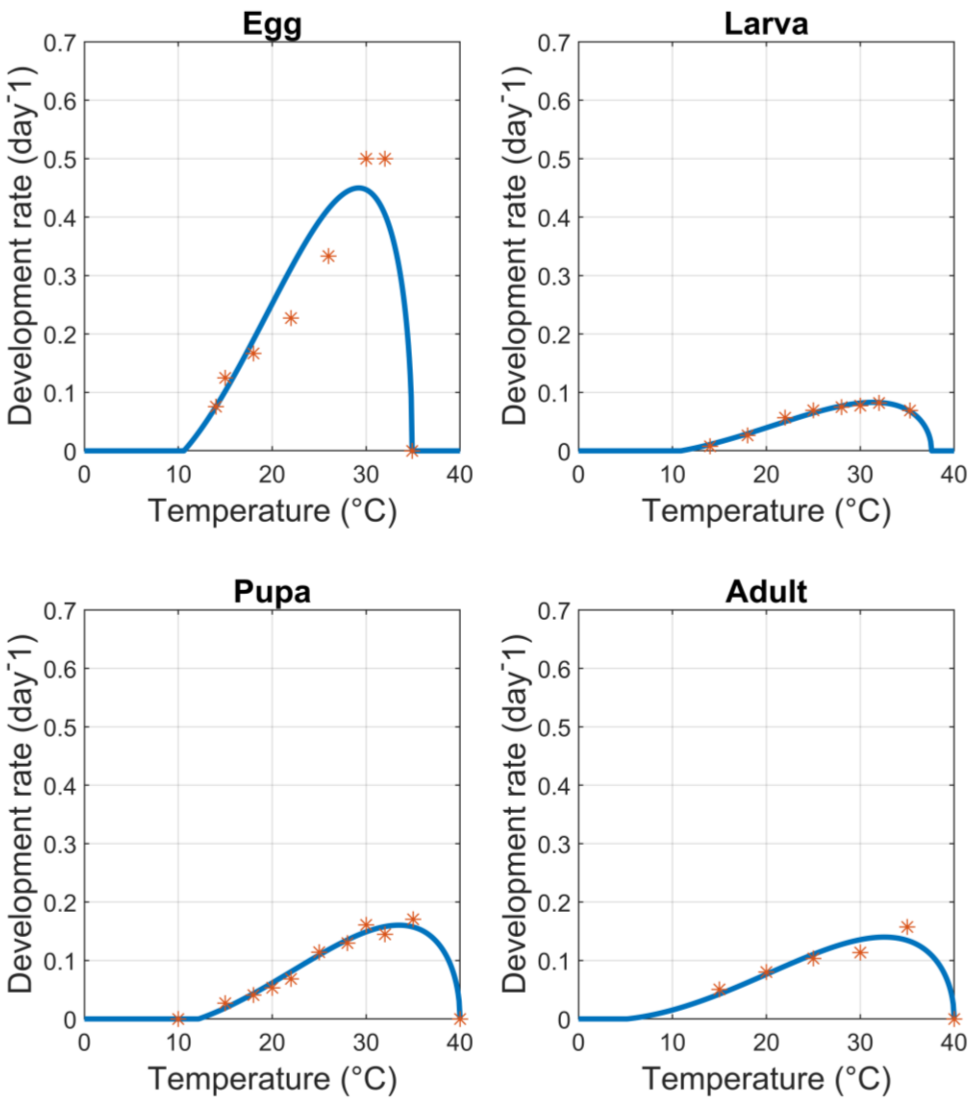

Fig.S1 Fitted development rate functions $v(T(t))$ (blue lines) on temperature for eggs, larvae, pupae, and adults of *Spodoptera frugiperda*. Red asterisks refer to data on *S. frugiperda* development rates calculated at different constant temperatures

S1.2. Mortality rate function

The stage-specific mortality rate function $m(t)$ was estimated starting from data referring to the average stage-specific percentage survival measured at different constant temperatures. These data allowed calculating the stage-specific temperature-dependent finite mortality rate $M(T(t))$ (i.e., the percentage of mortality in a stage at a given temperature T at time t)

$$M\big(T(t)\big) = \begin{cases} k & T(t) < T^{\mu}_{inf} \\ p_1 T^2 + p_2 T + p_3 & T^{\mu}_{inf} \leq T(t) \leq T^{\mu}_{sup} \\ k & T(t) > T^{\mu}_{sup} \end{cases}$$

where T^{μ}_{inf} and T^{μ}_{sup} are the minimum and maximum temperatures so that $M\big(T(t)\big)$ assumes the maximum value $k = 0.9$ representing the hypothesised maximum mortality within a stage. As no data were available for the adult stage, we assumed $M^3\big(T(t)\big) = M^4\big(T(t)\big)$. Parameters of the finite mortality rate $M\big(T(t)\big)$ and related figures for each stage are reported in Table S2 and Figure S2. Then, we estimated the temperature-dependent instantaneous mortality $\mu\big(T(t)\big)$ derived from the finite mortality using the following

$$\mu\big(T(t)\big) = \begin{cases} c_{L1}\,(T(t) - T^{\mu}_{inf}\,)^2 \;+\; c_{L2}(T(t) - T^{\mu}_{sup}\,) \;+\; c_{L3} & T(t) < \; T_{inf} \\ -v(T(t))\log(1 - M(T(t))) & T_{inf} \leq T(t) \leq T_{inf} \\ c_{R1}\,(T(t) - T^{\mu}_{inf}\,)^2 \;+\; c_{R2}(T(t) - T^{\mu}_{sup}\,) \;+\; c_{R3} & T(t) > T_{sup} \end{cases}$$

with parameters c_{Ln} and c_{Rn}, $n = 1, 2, 3$ of the outer branches of $\mu\big(T(t)\big)$ were inferred to obtain the desired slope of the curve and a sufficiently regular connection with the middle branch ($\mu\big(T(t)\big)$ of class C^1). The mortality rate function $m(t)$ for the stages $i = 1, 3, 4$ depends on temperature through the following law

$$m(t) = \mu\big(T(t)\big)$$

Parameters of the instantaneous mortality rate function $\mu\big(T(t)\big)$ and related figures for each stage are reported in Table S3 and Figure S3. In the present work, the mortality rate function $m(t)$ of stage $i = 2$ is expressed as follows

$$m^i(t) = \mu^i\big(T(t)\big)\left(1 + \alpha\left(\frac{N^i(t)}{\gamma}\right)^2\right) + \beta$$

with $\left(1 + \alpha\left(\frac{N^i(t)}{\gamma}\right)^2\right)$ representing a density-dependent component simulating the intraspecific competition (e.g., cannibalistic behaviour), $\alpha > 0$ representing a multiplicative term, and $\beta > 0$

representing a biotic component simulating the role of predators, parasites and pathogens. The parameter $\gamma > 0$ represents the larval carrying capacity based on resources availability.

Table S2 Estimated parameters p_1, p_2 and p_3 of the temperature-dependent finite mortality rate $M(T(t))$ for eggs, larvae, pupae, and adults of *Spodoptera frugiperda*

Stage	$\boldsymbol{p_1}$	$\boldsymbol{p_2}$	$\boldsymbol{p_3}$
Eggs	0.0049	-0.2233	2.5616
Larvae	0.0054	-0.2803	3.8368
Pupae	0.0037	-0.1927	2.6224
Adults	0.0037	-0.1927	2.6224

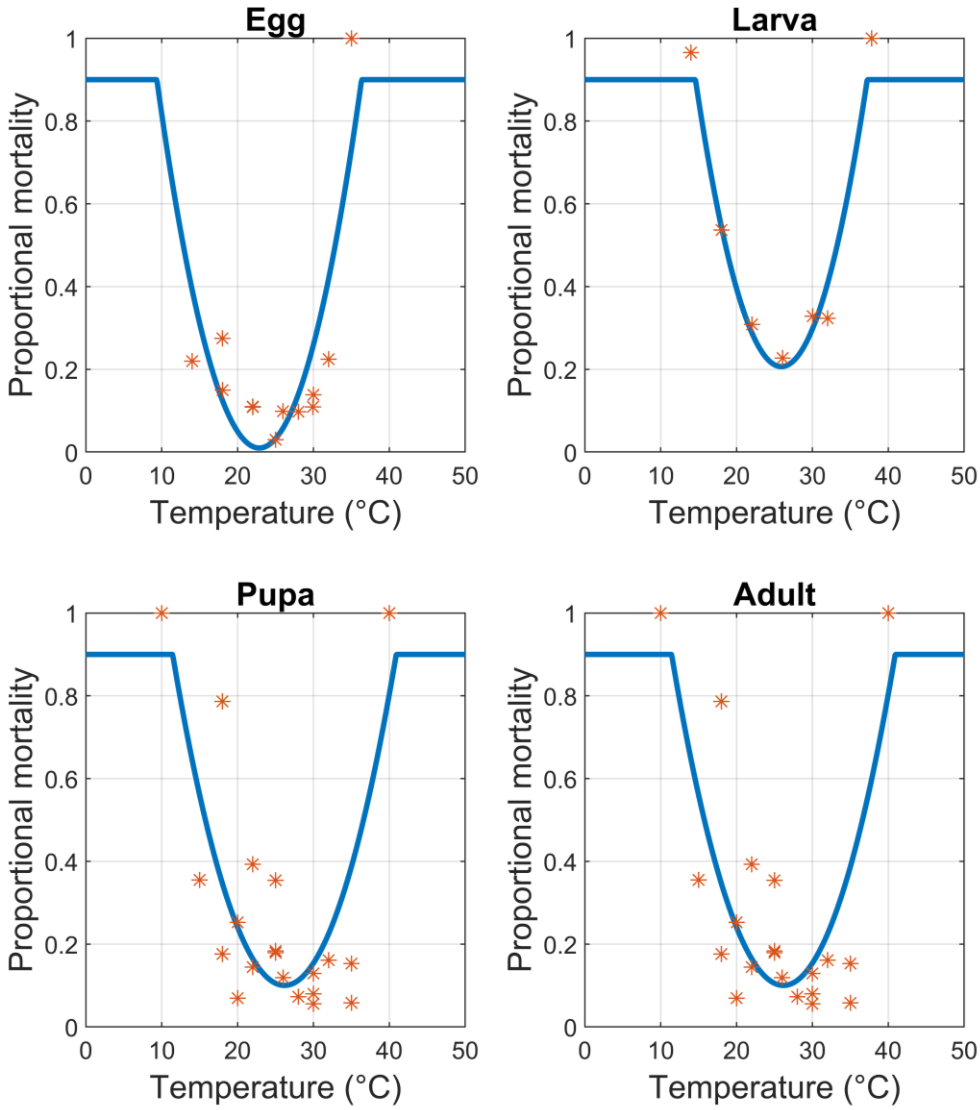

Fig.S2 Fitted finite mortality rate functions $M(T(t))$ (blue lines) on temperature for eggs, larvae, pupae, and adults of *Spodoptera frugiperda*. Red asterisks refer to data on *S. frugiperda* survival at different constant temperatures

Table S3 Estimated parameters c_{L1}, c_{L2}, c_{L3}, c_{R1}, c_{R2}, c_{R3}, T_{inf}^{μ} and T_{sup}^{μ} of the temperature-dependent instantaneous mortality $\mu\big(T(t)\big)$ for eggs, larvae, pupae, and adults of *Spodoptera frugiperda*

Stage	c_{L1}	c_{L2}	c_{L3}	c_{R1}	c_{R2}	c_{R3}	T_{inf}^{μ} (ºC)	T_{sup}^{μ} (ºC)
Eggs	0.0041	-0.1589	1.5706	0.0056	-0.3083	4.3236	18.75	31.27
Larvae	0.008	-0.2408	1.8348	0.0276	-1.8867	32.3157	14.6	34.39
Pupae	0.0032	-0.1375	1.4991	0.0485	-3.4621	61.826	21.38	35.82
Adults	0.0166	-0.3879	2.2853	0.0503	-3.58	63.7595	11.45	35.65

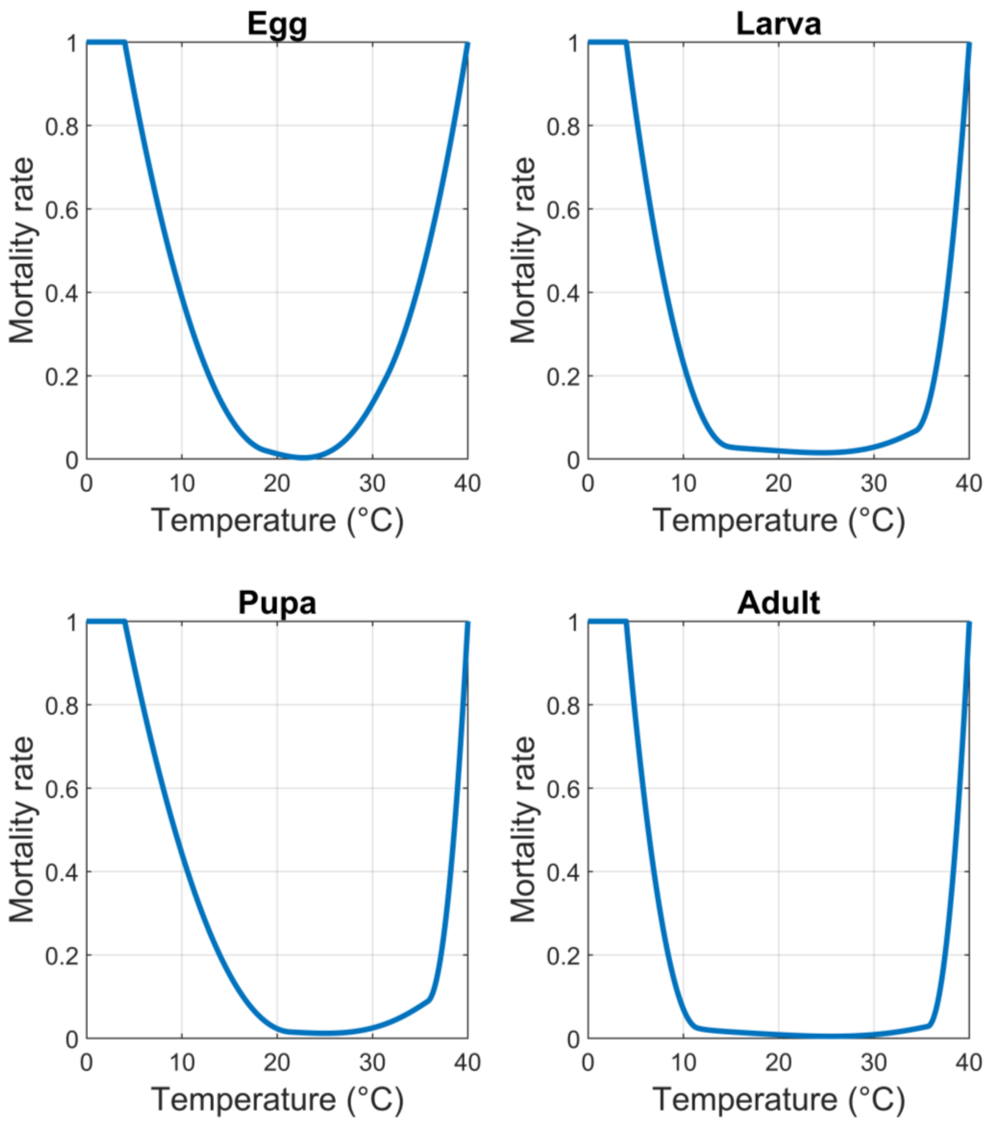

Fig.S3 Fitted instantaneous mortality rate functions $\mu\big(T(t)\big)$ (blue lines) on temperature for eggs, larvae, pupae, and adults of *Spodoptera frugiperda*

S1.3. Fecundity rate function

The temperature-dependent component $g\big(T(t)\big)$ of the fecundity rate function $F^1(t)$ was estimated through the following

$$g\big(T(t)\big) = \begin{cases} r^F T(t)\big(T(t) - T_{inf}^F\big)\sqrt{T_{sup}^F - T(t)} & T_{inf}^F \leq T(t) \leq T_{sup}^F \\ 0 & otherwise \end{cases}$$

Parameters were estimated through the least squares method on experimental data referring to average total fecundity, average daily fecundity, and average duration in days of the oviposition period measured at different constant temperatures. The parameter r^F is a scaling parameter, T_{inf}^F and T_{sup}^F represent the minimum and maximum temperature thresholds at which egg-laying occurs. Based on the data provided in (Murúa and Virla 2004) we calculated the physiological age at which the maximum amount of eggs is produced by a female $x_{opt} = 0.23$ and the physiological age at which egg-laying ends (senescence) $x_{end} = 0.92$.

Then, the physiological age-dependent component $h(x)$ was estimated through the following

$$h(x) = \frac{x^{a-1}e^{bx}}{\|x^{a-1}e^{bx}\|_{L(0,1)}}$$

with positive parameters a and b obtained to guarantee that the maximum egg-laying occurs at $x_{opt} = 0.23$

$$x_{opt} = \frac{a-1}{b} = 0.23$$

and that

$$\int_0^{x_{end}} x^{a-1}e^{-bx}dx = \frac{99}{100}\int_0^1 x^{a-1}e^{-bx}dx$$

The resulting parameters are $a = 3.18$ and $b = 9.48$

The fitted temperature-dependent component $g\big(T(t)\big)$ and the physiological age-dependent component $h(x)$ of the fecundity rate function $F^1(t)$ of the adult stage is presented in Figure S4.

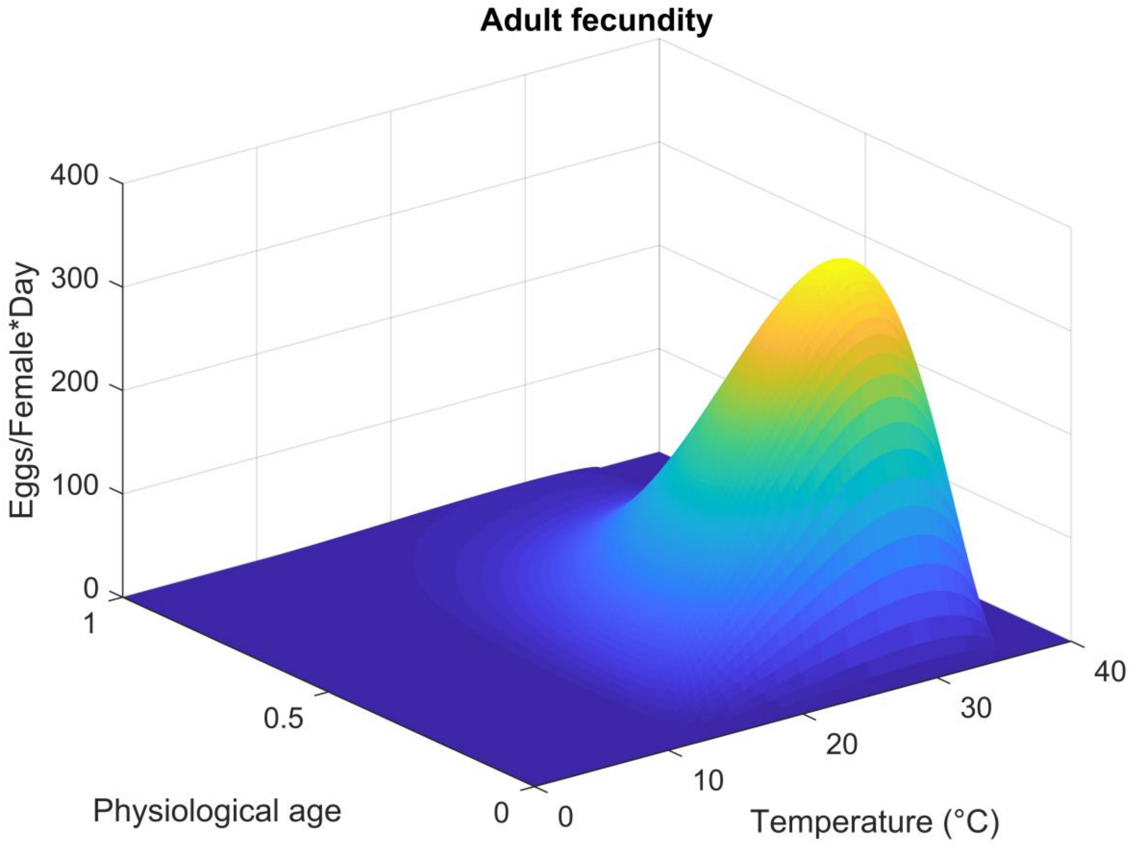

Fig.S4 Graph showing the temperature-dependent component $g(T(t))$ and the physiological age-dependent component $h(x)$ of the fecundity rate function $F^1(t)$ for the adult stage of *Spodoptera frugiperda*

S2. Correlation test between simulated and measured air temperature data

In Table S4 and Figure S5 are reported the results of the monthly-wise Pearson correlation test between scenario and observed air temperature data. Scenario data refer to bias-adjusted, 2-meters air temperature (monthly averages on the 2016-2025) data generated by CNRM-CERFACS within the CMIP5 (Coupled Model Intercomparison Project Phase 5) Project. Observed air temperature (monthly averages on 2010-2019) data are extracted from the E-OBS 21.0e Dataset (Cornes et al. 2018). The correlation test was performed on a subset of 10% of randomly selected grid points.

Table S4 Results of the monthly-wise Pearson correlation test between air temperature data related to the current climatic scenario (monthly averages on the 2016-2025 period) and observed air temperature data (monthly averages on the 2010-2019 period)

Month	**rho**	**p-value**
Jan	0.948	<0.001
Feb	0.956	<0.001
Mar	0.959	<0.001
Apr	0.973	<0.001
May	0.968	<0.001
Jun	0.963	<0.001
Jul	0.970	<0.001
Aug	0.977	<0.001
Sep	0.976	<0.001
Oct	0.972	<0.001
Nov	0.975	<0.001
Dec	0.952	<0.001

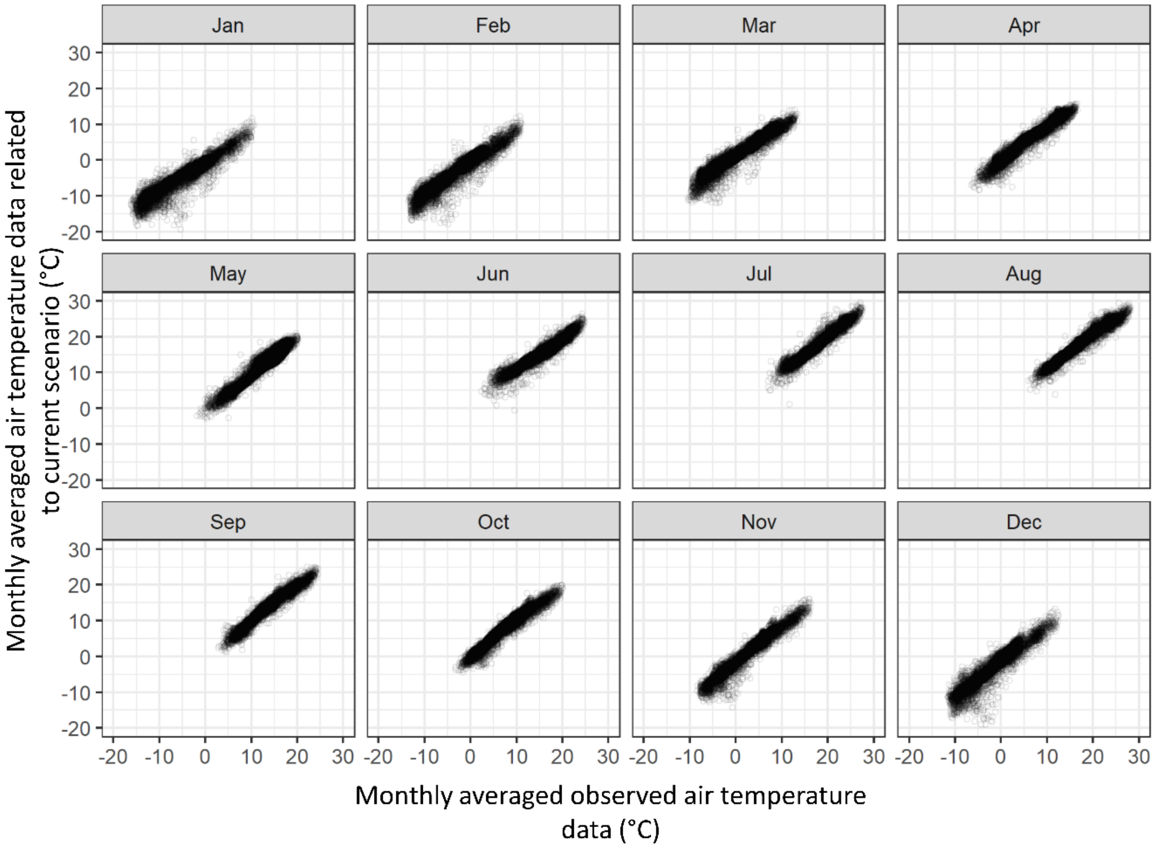

Fig.S5 Scatter-plot showing the monthly-wise correlations between air temperature data related to the current climatic scenario (monthly averages on the 2016-2025 period) and observed air temperature data (monthly averages on the 2010-2019 period)

S3. Parameters estimates for each location of the calibration dataset

Table S5 Estimates of parameters α and β of the mortality rate function for larvae $m^2(t)$ of *Spodoptera frugiperda* and Mean Squared Error (MSE) resulting from the calibration procedure implemented in each location of the calibration dataset

Id location	$\boldsymbol{\alpha}$	$\boldsymbol{\beta}$	**MSE**
1	1.680	0.400	63.728
2	5.000	0.019	3008.630
3	4.448	0.396	471.039
4	5.000	0.192	4122.043
5	4.985	0.177	61.669
6	0.838	0.309	5147.818
7	0.637	0.223	4109.185
8	4.040	0.177	11012.545
9	0.633	0.203	16505.461
10	5.000	0.400	714.327
11	5.000	0.400	469.142
12	5.000	0.328	623.367
13	3.210	0.400	6056.979
14	5.000	0.304	2699.600
15	0.500	0.010	141747.361
16	0.517	0.010	16530.343
17	0.615	0.254	6326.576
18	5.000	0.204	2254.815
19	5.000	0.182	682.317
20	5.000	0.166	1457.994
21	2.457	0.317	1587.010

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